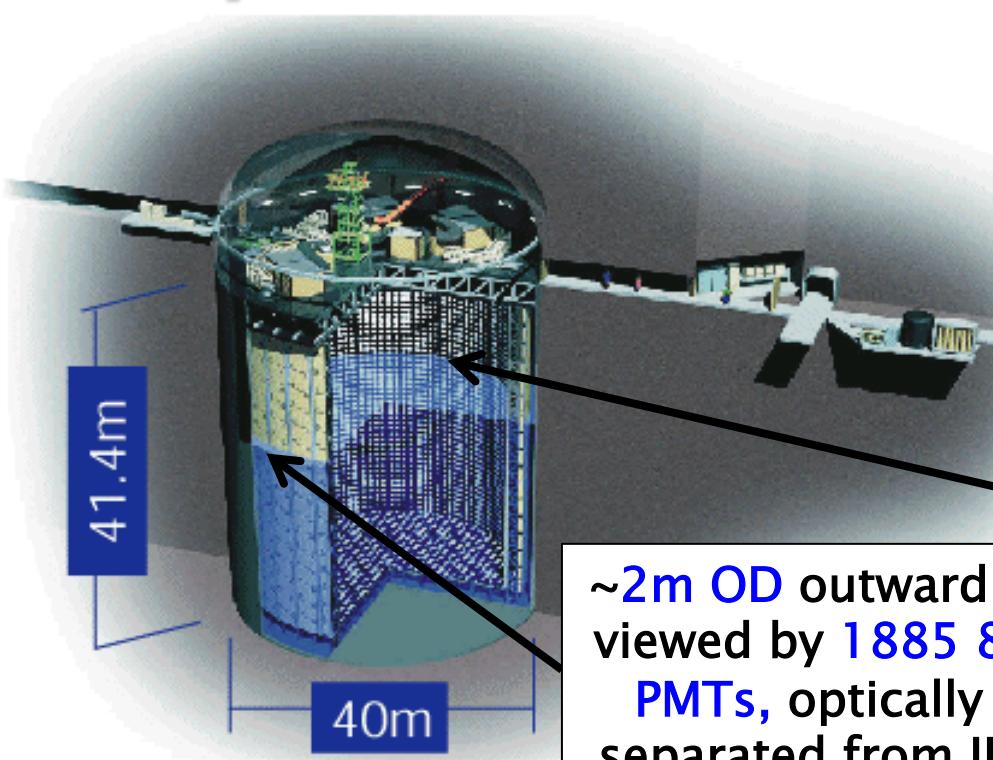


Solar Neutrino Results from Super-Kamiokande



Andrew Renshaw, for the SK Collaboration
University of California, Irvine
Tuesday September 10th, 2013

Super-Kamiokande

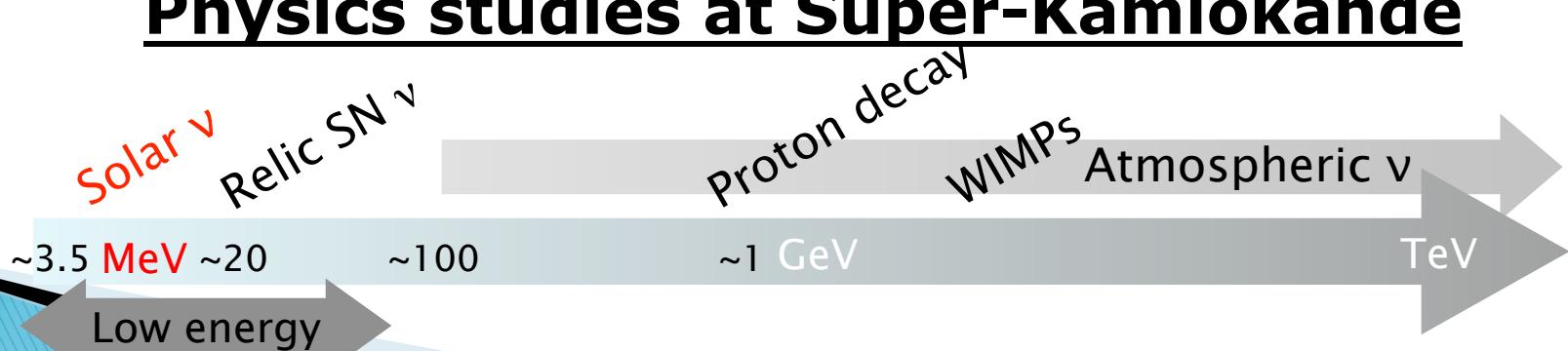


- 50 kton pure water Cherenkov detector
- 1 km (2700 mwe) underground

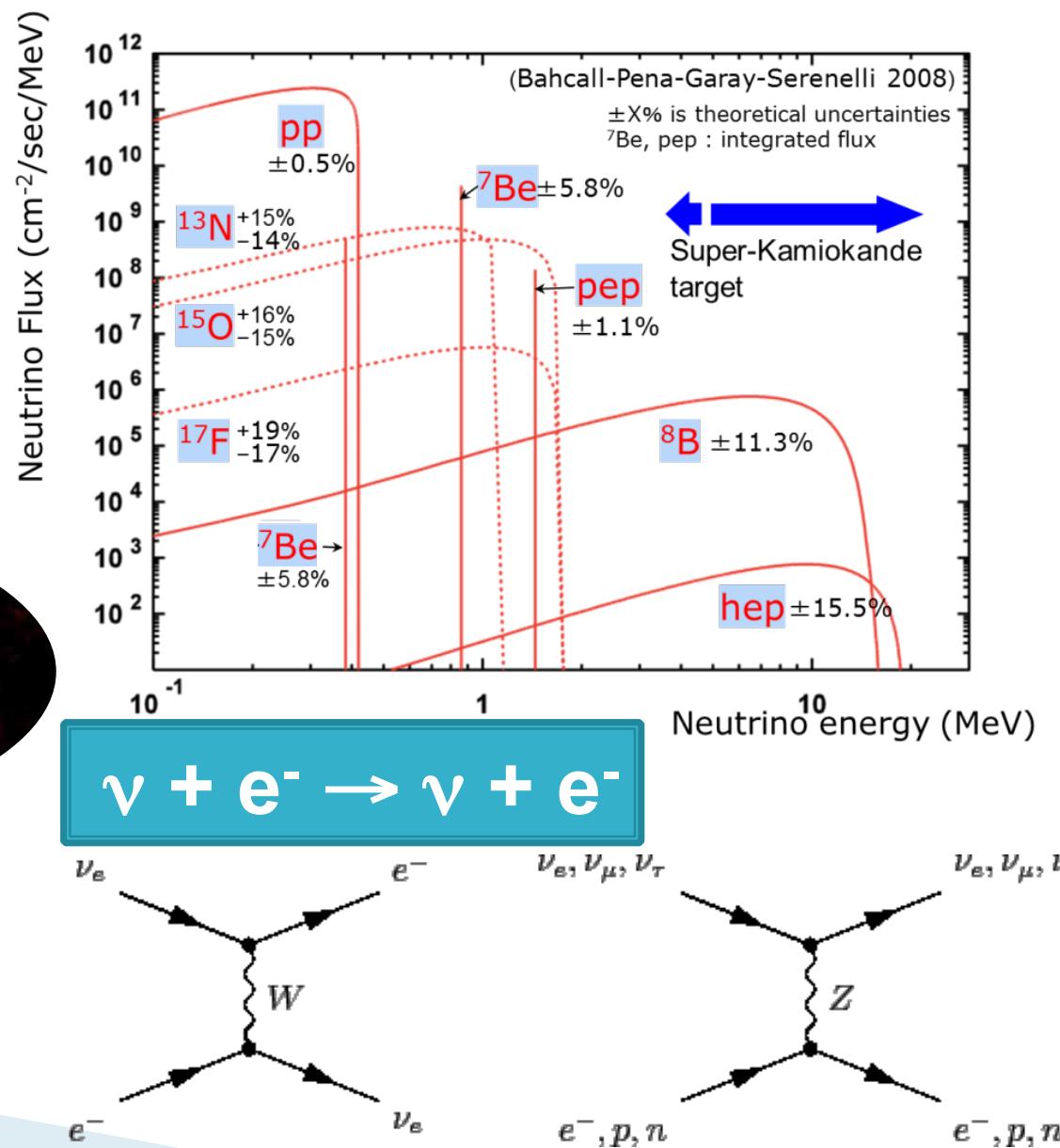
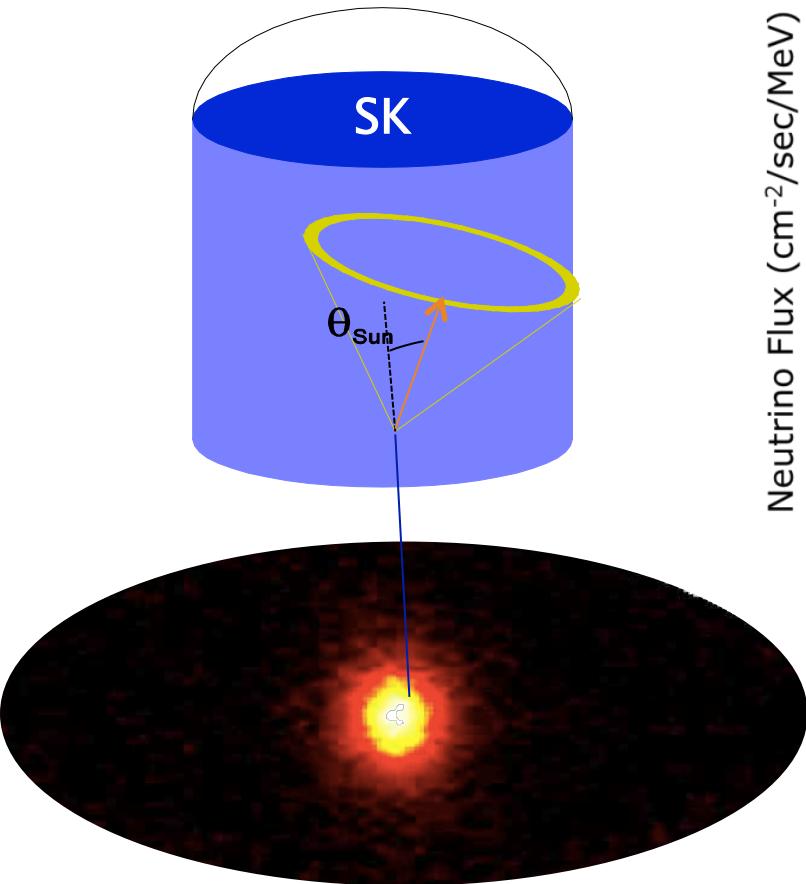
ID inwardly viewed by
11,129 20" PMTs (40%
coverage, single photon
sensitivity),
32kton->22.5kton FV

~2m OD outwardly
viewed by 1885 8"
PMTs, optically
separated from ID

Physics studies at Super-Kamiokande

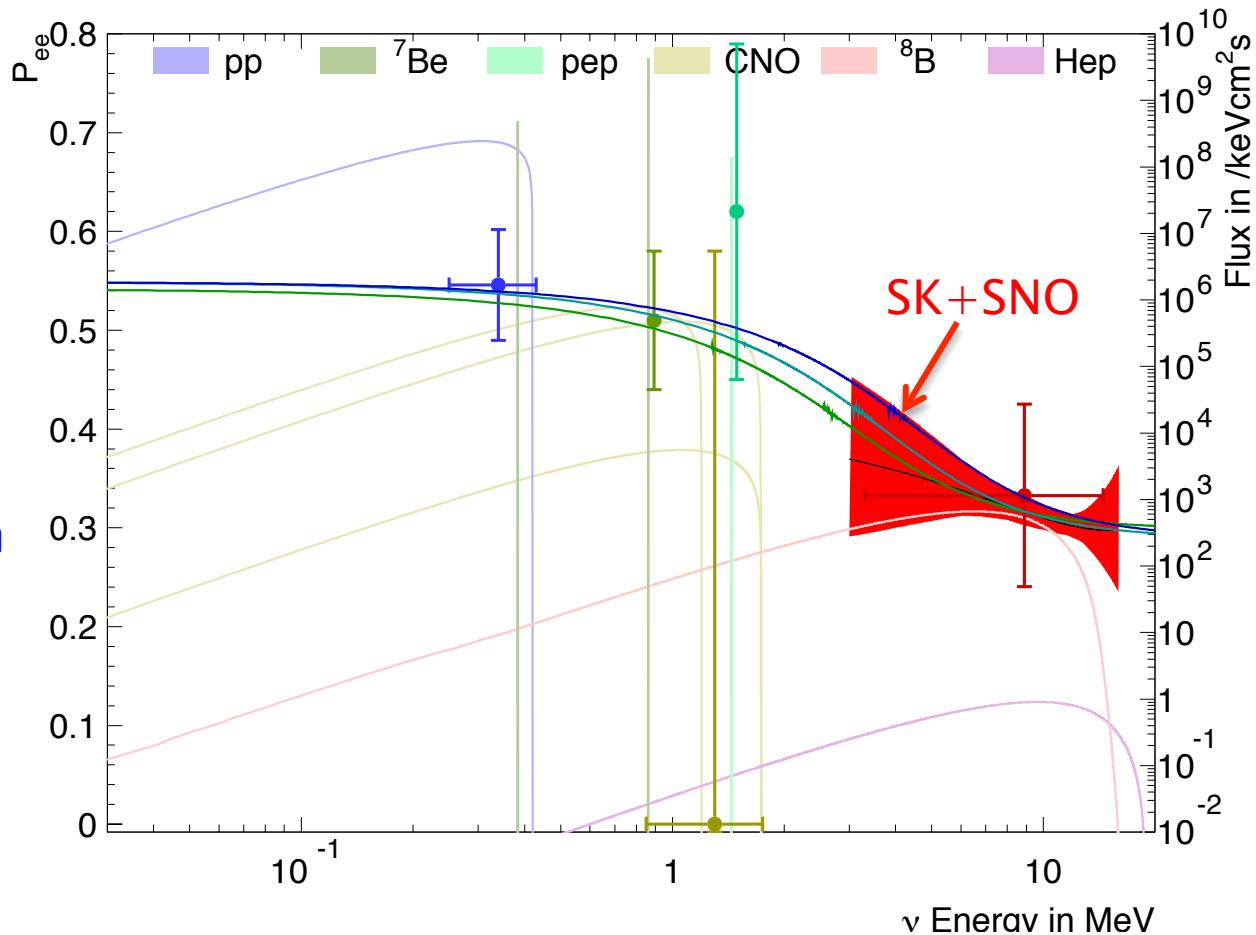


Solar Neutrinos in SK



Spectrum Upturn

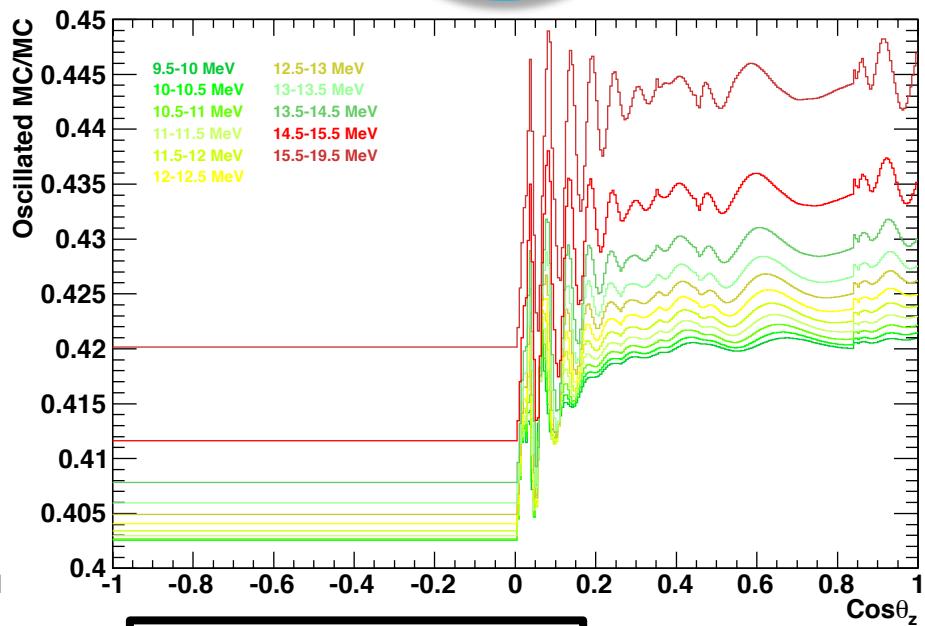
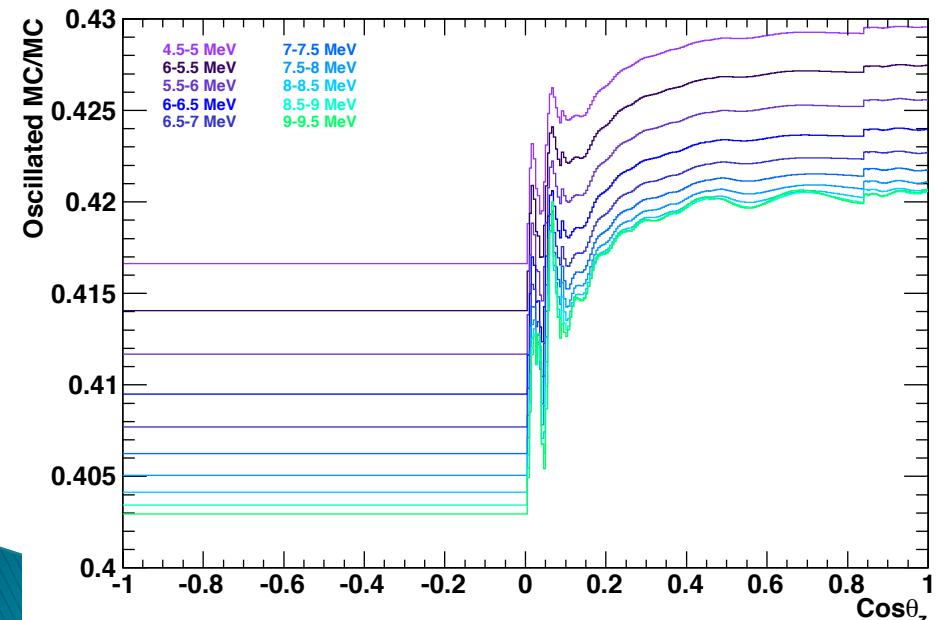
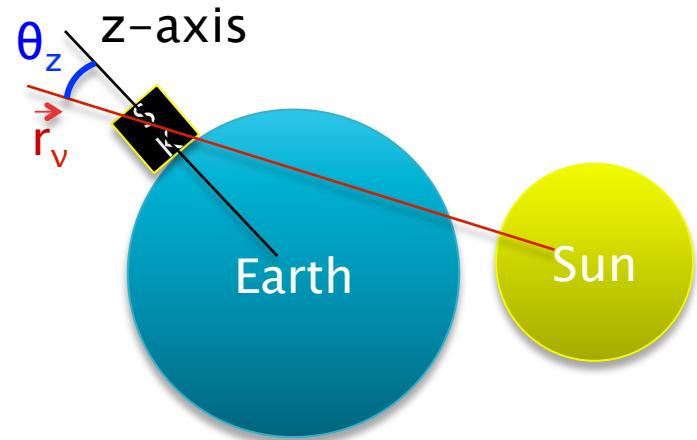
- ▶ The **MSW resonance** will lead to the energy dependence of the ν_e survival probability, with the signature “**upturn**”
- ▶ Survival probability- $\rightarrow^{8}\text{B}$ solar neutrino elastic scattering **recoil electron energy spectrum**
- ▶ SK can search for the “**upturn**” in its **recoil electron energy spectrum**



- ▶ Other factors can also distort the SK recoil electron energy spectrum
 - Solar *hep* ν 's observed in the high energy end
 - Energy dependence of time variation oscillation effects
 - Energy dependence of differential cross sections

Solar Neutrino Day/Night Effect

- Regeneration of ν_e 's during the night (asymmetry in the day and night ES interaction rates)

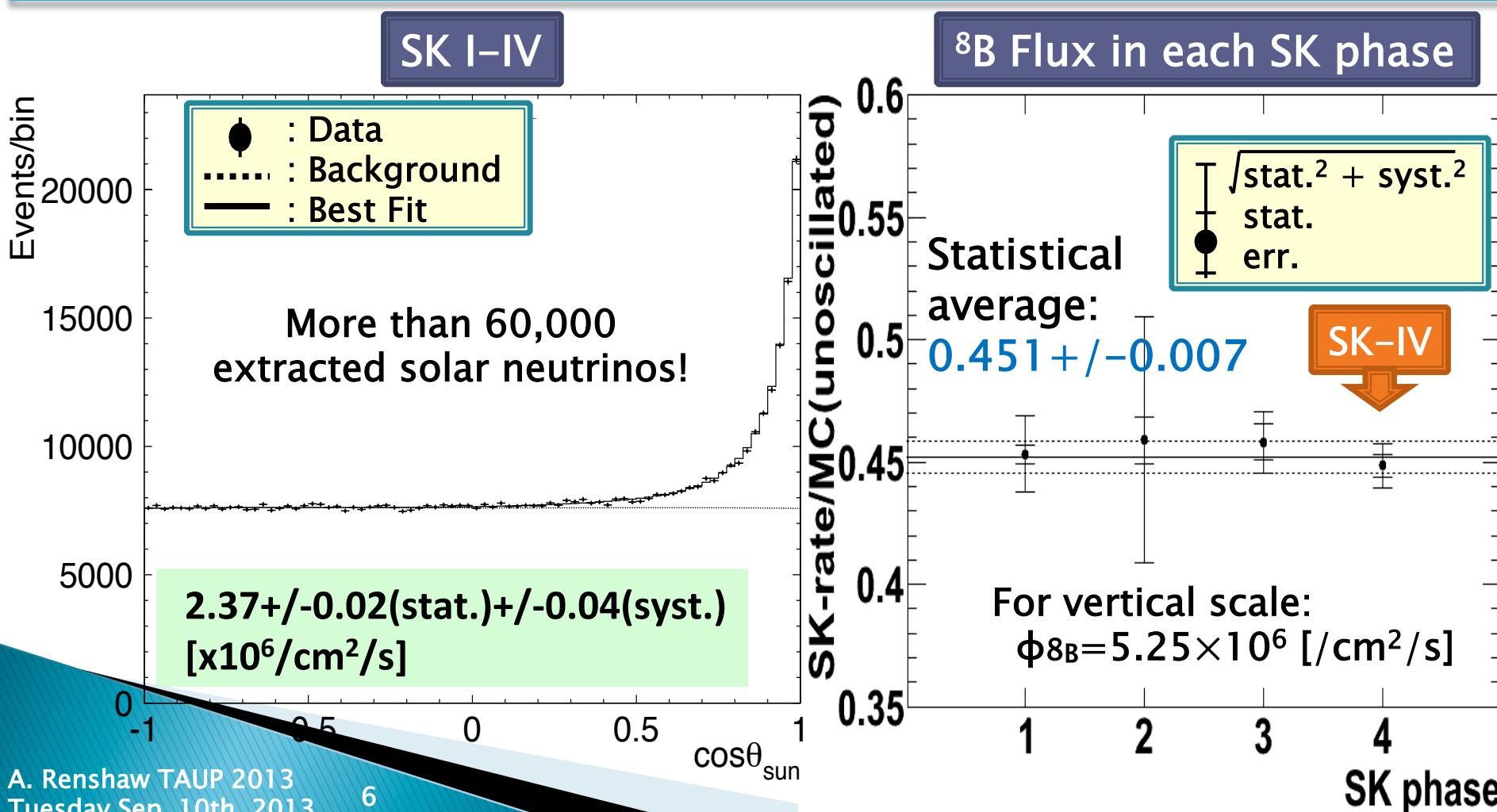


$$\Delta m_{21}^2 = 4.9 \times 10^{-5} \text{ eV}^2$$
$$\sin^2 \theta_{12} = 0.314$$

8B Solar Neutrino Flux

SK-IV Improvements

- Better water quality control
- New electronics
- New multiple scattering parameter
- Reduced systematic error
1.7% for flux cf. SK-I: 3.2% SK-III: 2.1%

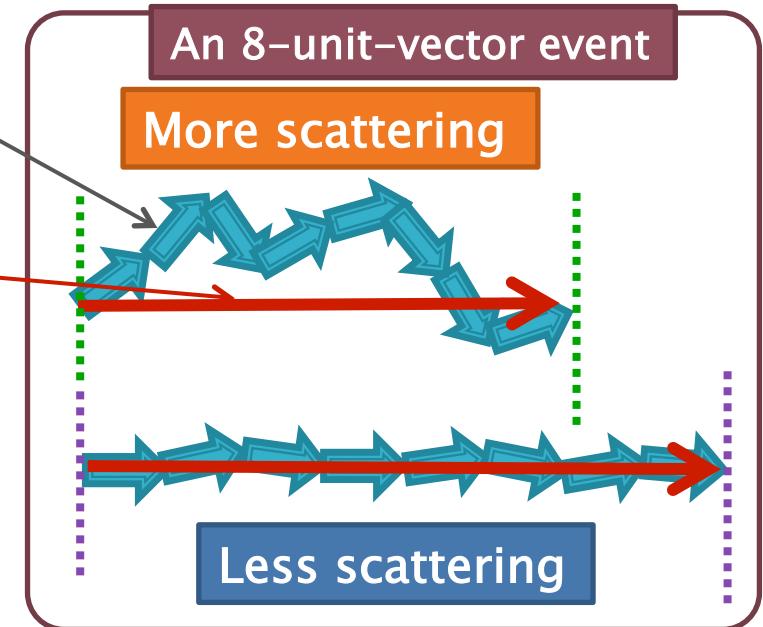


Multiple Scattering Goodness

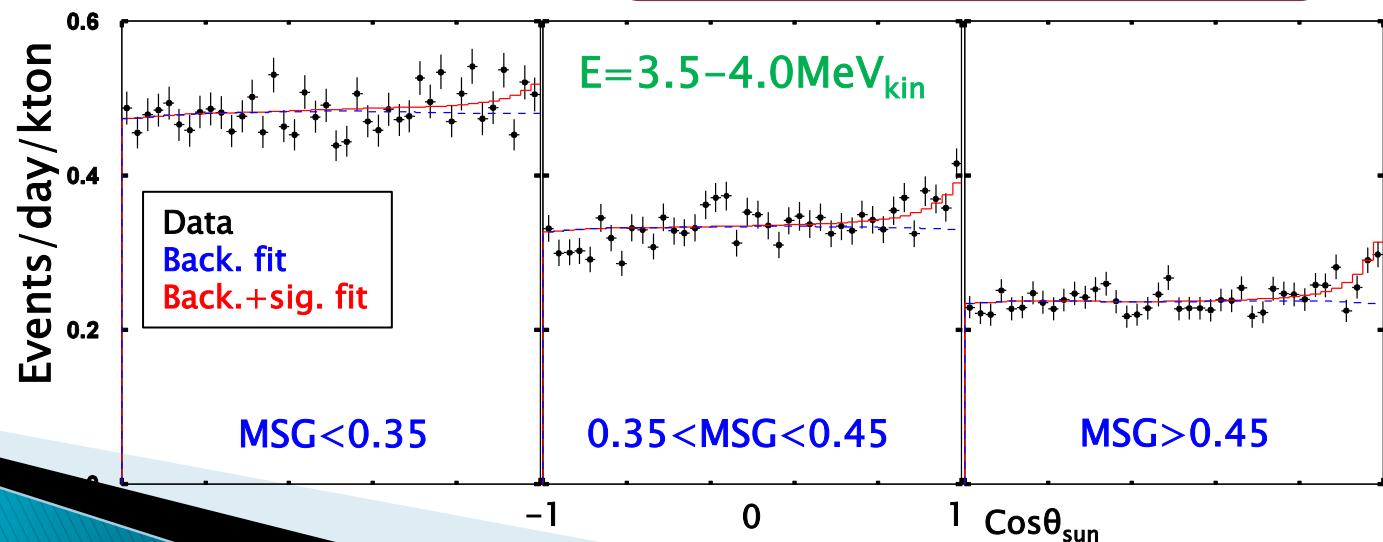
“unit vectors” (test directions from Hough transformation of PMT pairs, within 20ns hit PMTs, within 50°)

“best direction”
(longest vector sum of unit vectors)

$$\text{MSG} = \frac{\text{Length of best direction}}{\# \text{ of unit vectors}}$$

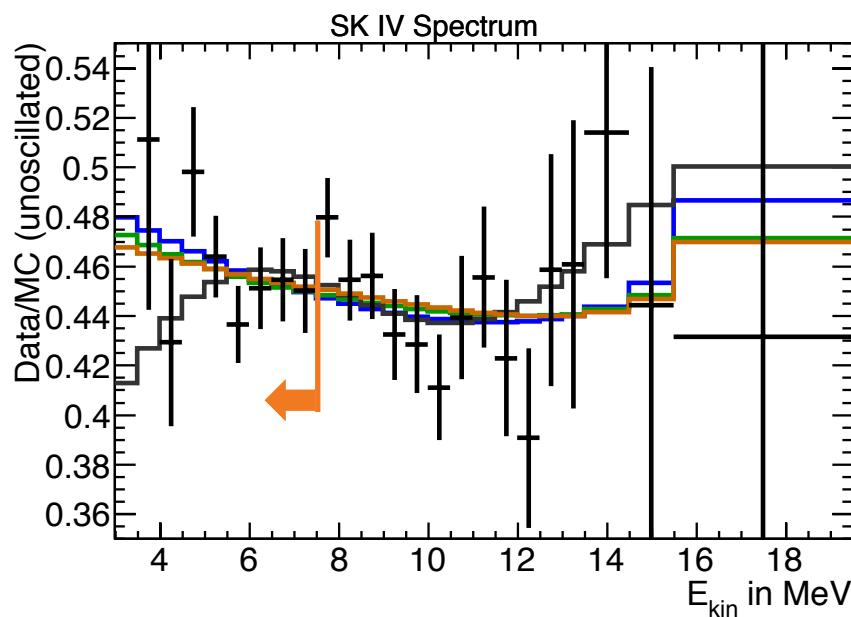
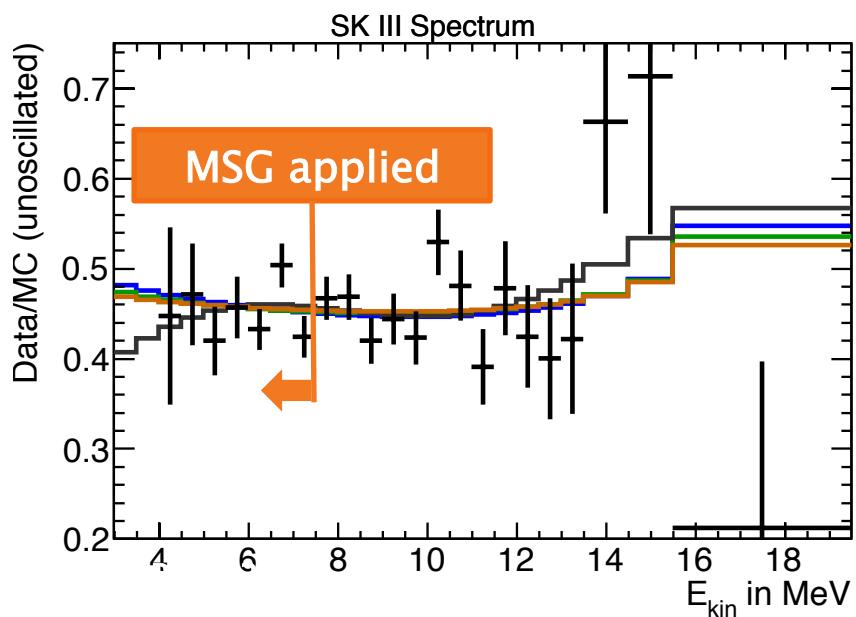
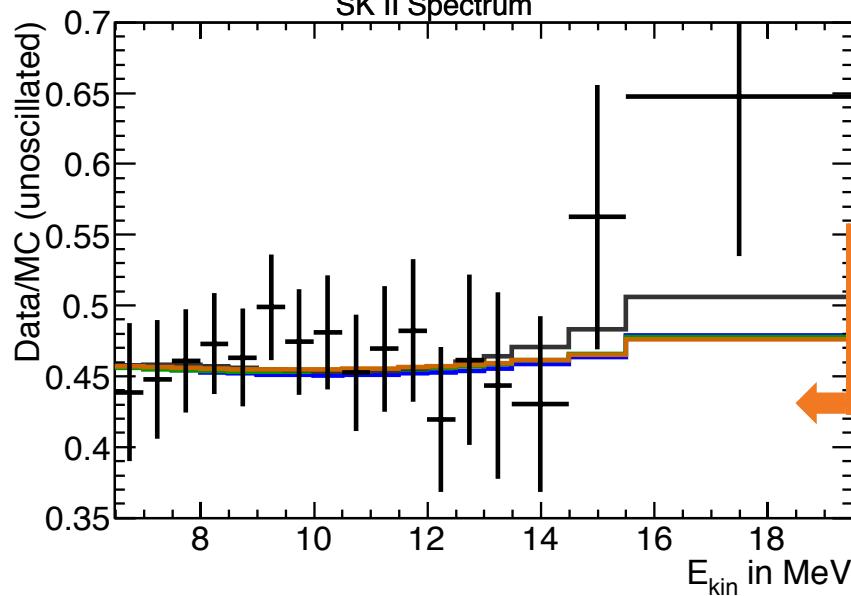
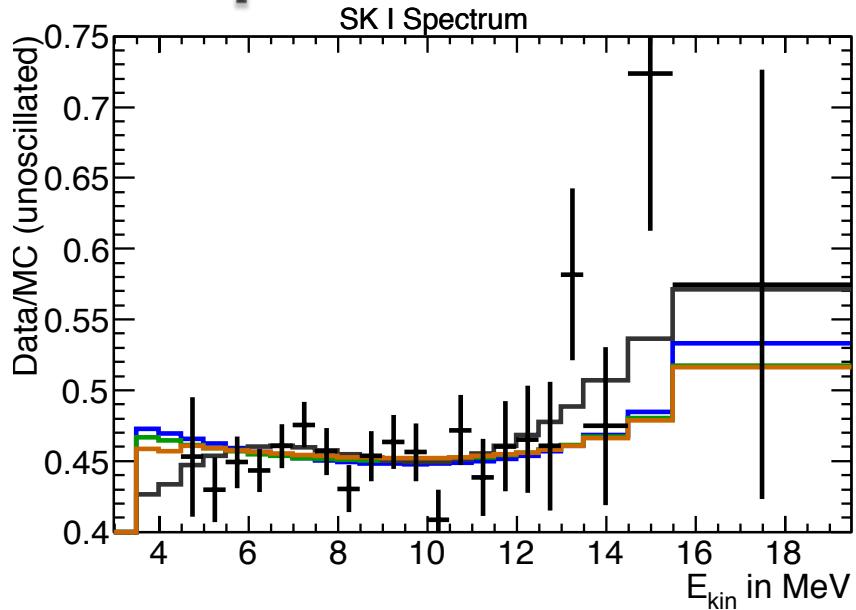


Simultaneous fit to three MSG bins, ratio of signal determined by MC

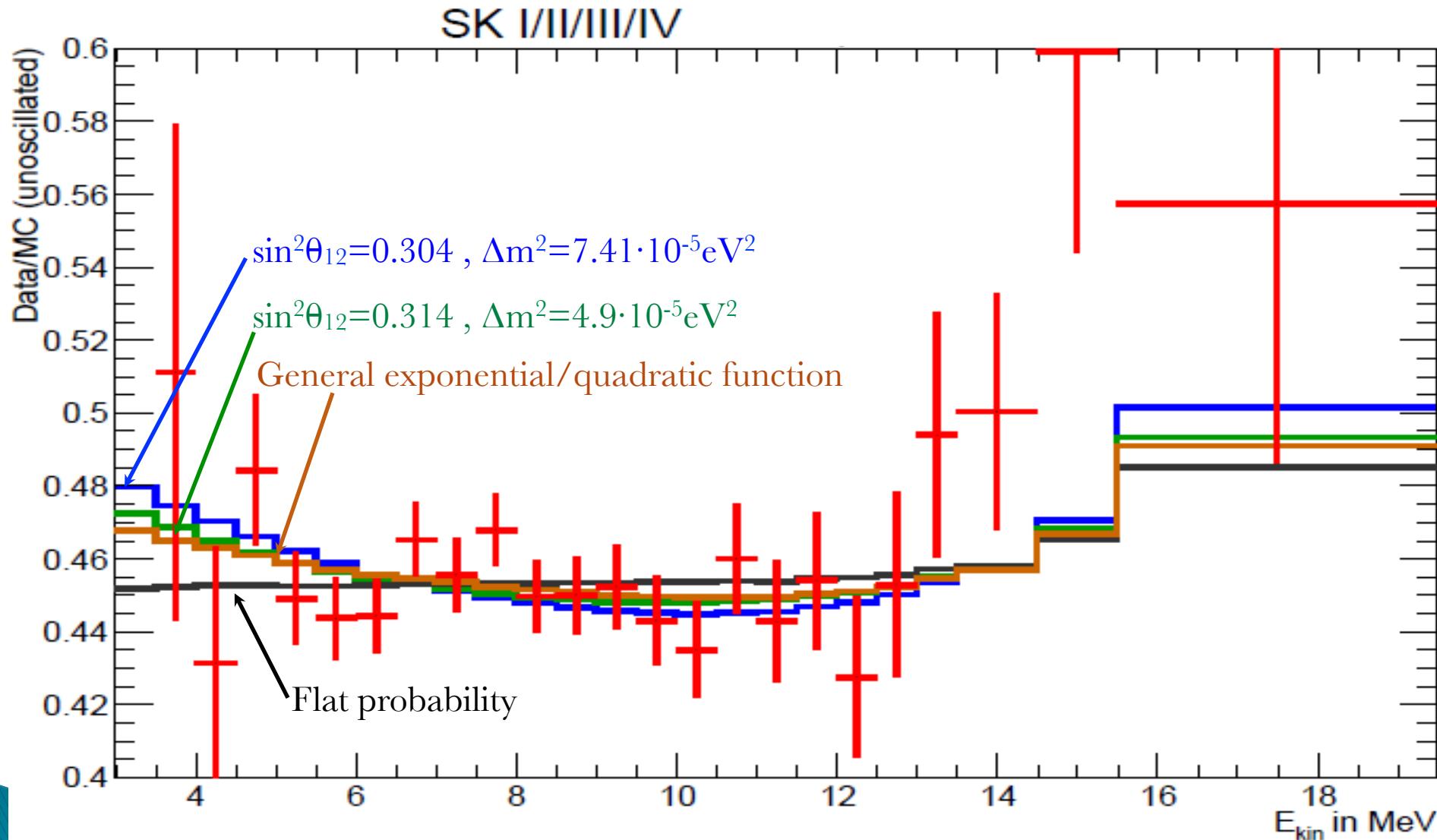


SK Spectra

For vertical scale:
 $\phi_{8B} = 5.25 \times 10^6 / \text{cm}^2/\text{s}$

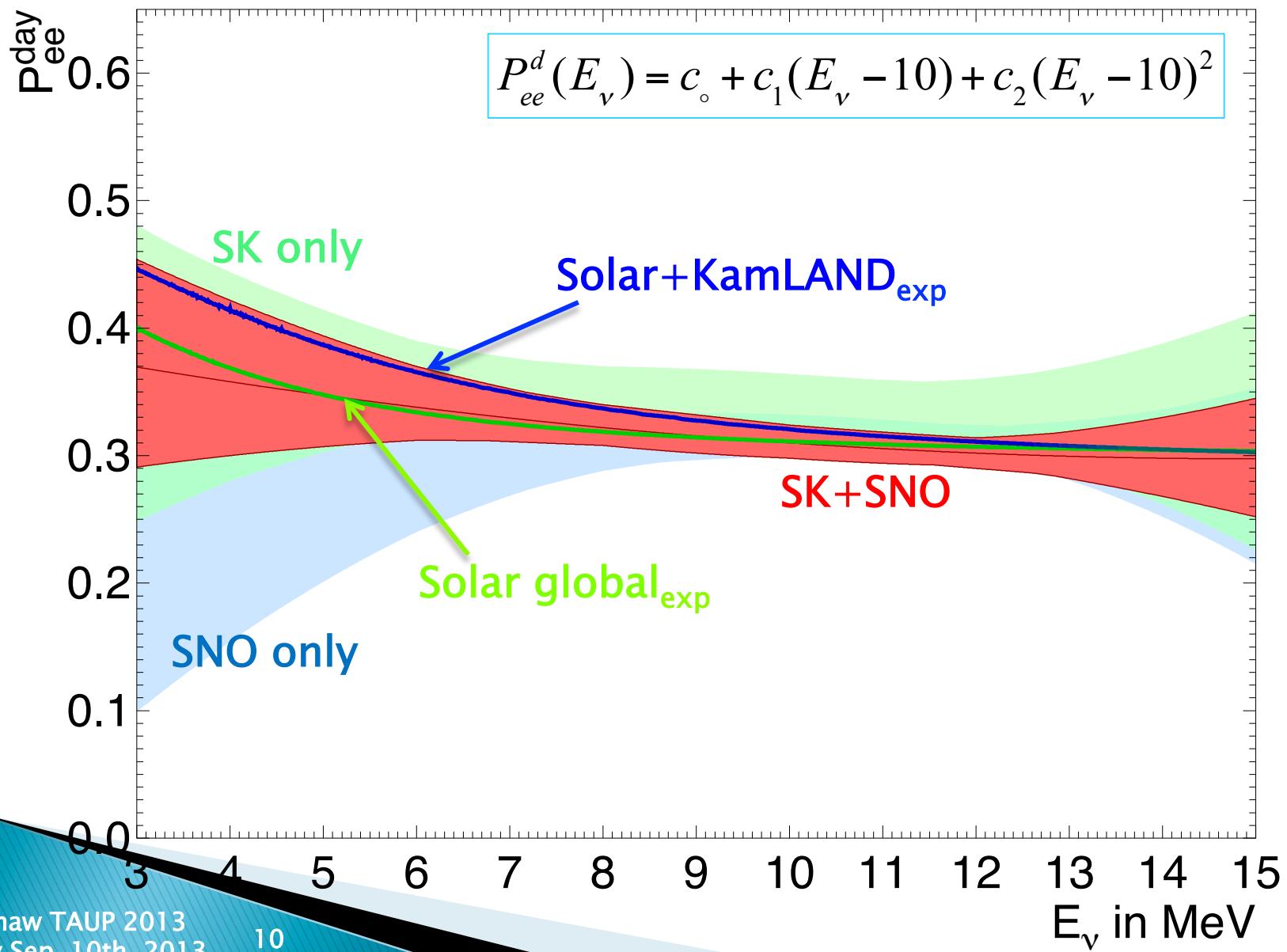


MSW to Vacuum Oscillation Upturn?



Distorted shape is slightly favored

Allowed Survival Probability $P_{ee}(E_\nu)$



(1) Searching For The Day/Night Effect

- ▶ Simplest method **extracts the day and night fluxes separately** ($\text{day} = \cos\theta_z < 0$, $\text{night} = \cos\theta_z \geq 0$)
- ▶ The **day/night asymmetry** is then formed as

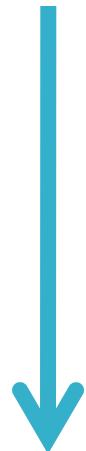
$$A_{DN} = \frac{\Phi_D - \Phi_N}{1/2(\Phi_D + \Phi_N)}$$

- ▶ This measurement assumes an average flux during the day and night times
- ▶ Measurement independent of osc. parameters

(2) Searching For The Day/Night Effect

$$\mathcal{L} = e^{-(\sum_i B_i + S)} \prod_{i=1}^{N_{bin}} \prod_{\nu=1}^{n_i} (\beta_i(c_\nu) B_i + \sigma_i(c_\nu) m_i S)$$

Solfit Likelihood



Modified Solfit Likelihood

- B_i : # of background events, energy bins i
- S : # of signal events
- $\beta_i[c_\nu = \cos(\theta_\nu^{\text{sun}})]$:background shapes
- σ_i : signal shapes (solar peak)

- m_i : MC ratio of energy bin i: $m_i = \frac{MC_i}{\sum_j MC_j}$

$$\mathcal{L} = e^{-(\sum_i B_i + S)} \prod_{i=1}^{N_{bin}} \prod_{\nu=1}^{n_i} (\beta_i(c_\nu) B_i + \sigma_i(c_\nu) \times z_i(t_\nu) m_i S)$$

New signal factor can include any time variable, such as solar zenith angle (day/night effect), distance sun-earth (eccentricity, seasonal), etc.

(2) Searching For The Day/Night Effect

The signal time variation factor is split into two parts, one depends on a **day/night amplitude** scaling factor α

$$z_i(t_v) \Rightarrow z_i(\alpha, t) = \frac{1 + \alpha((1 + a_i)r_i(t) / r_i^{\text{av}} - 1)}{1 + \alpha a_i} \times z_{\text{exp}}(t)$$

r_i^{av} = livetime averaged rate

$r_i(t)$ = rate in zenith bin of event

(from MC)

a_i = Effective day/night asymmetry

α = day/night scaling parameter

$Z_{\text{exp}}(t)$ takes into account eccentricity corrections and the day/night MC efficiency difference, does not depend on α

The day/night asymmetry A_{DN} is then given by:

$$A_{\alpha_i} = \frac{r_{\alpha_i}^{\text{day}} - r_{\alpha_i}^{\text{night}}}{1/2(r_{\alpha_i}^{\text{day}} + r_{\alpha_i}^{\text{night}})} = \alpha \times A_i$$



Expected day/night asymmetry
(osc. par. dependent)

DN Amplitude Fit 10 Year Anniversary

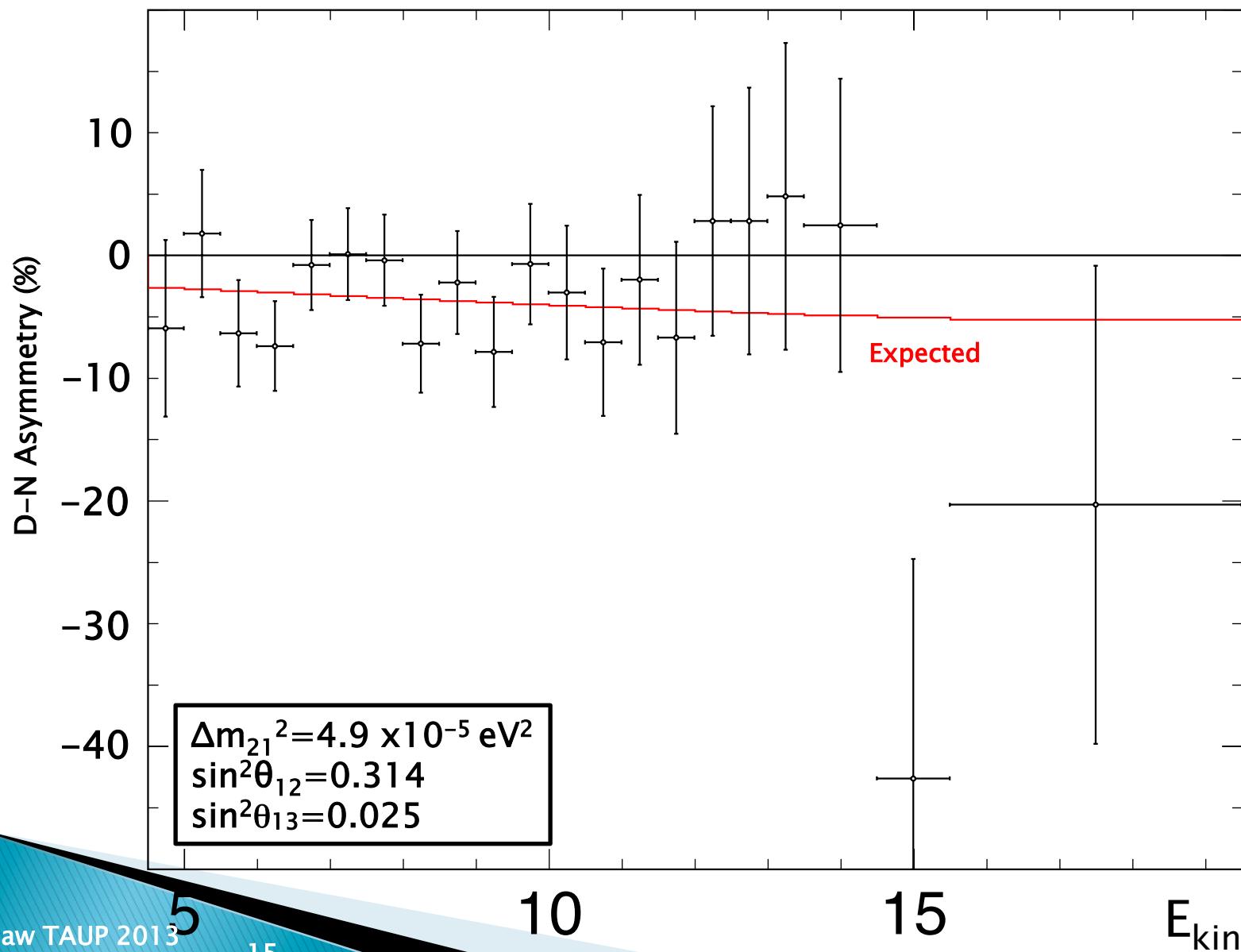
The Solar v Day/Night Effect in Super-Kamiokande

Michael B. Smy
University of California,
Irvine



at TAUP
^{5th}
September 2003,
Seattle

SK Day/Night Asymmetry



SK Day/Night Asymmetry

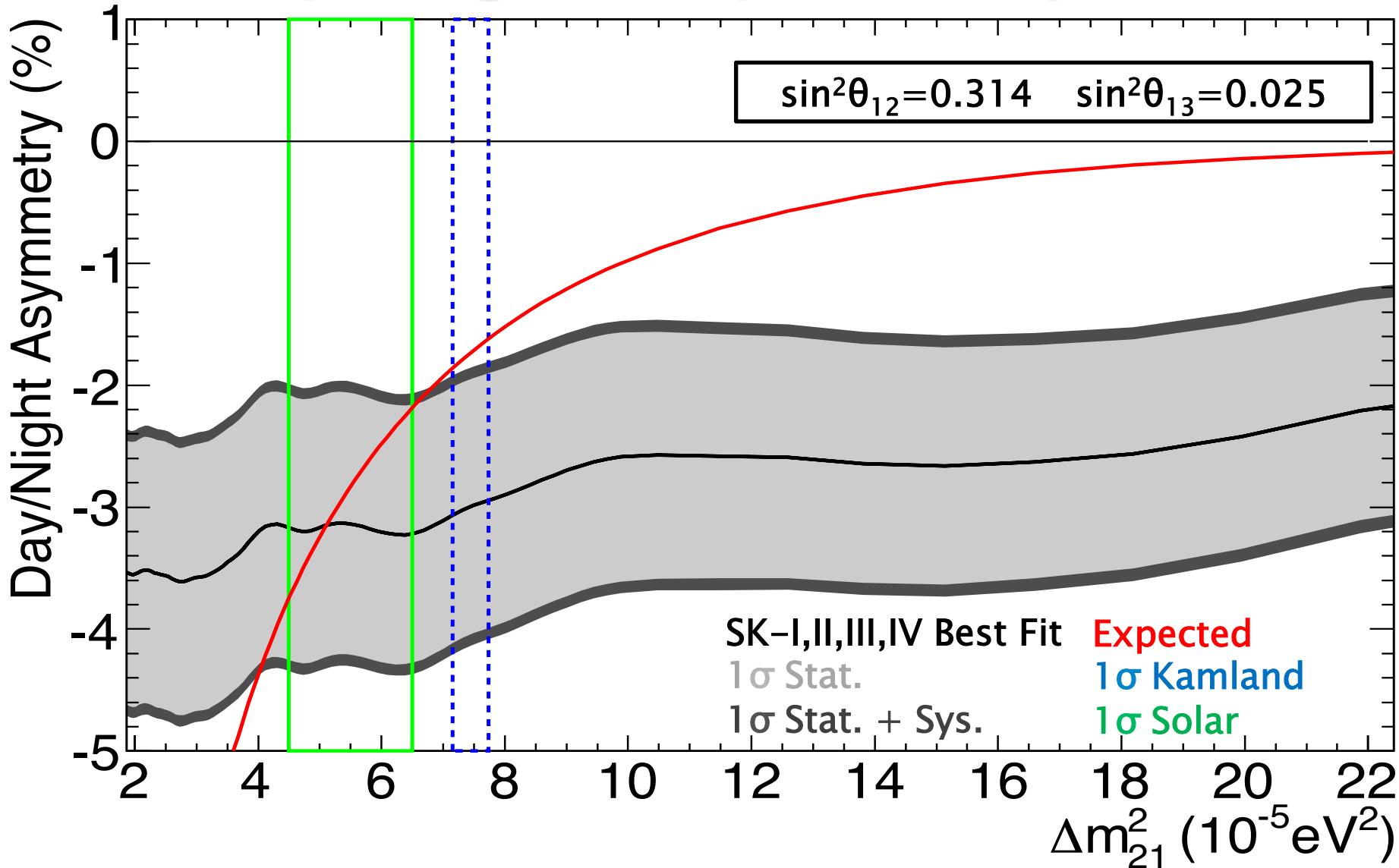
$$\Delta m_{21}^2 = 4.9 \times 10^{-5} \text{ eV}^2 \quad \sin^2 \theta_{12} = 0.314 \quad \sin^2 \theta_{13} = 0.025$$

	Straight Asymmetry	Ampfit
SK-I	-2.1±2.0±1.3%	-2.0±1.7±1.0%
SK-II	-5.5±4.2±3.7%	-4.3±3.8±1.0%
SK-III	-5.9±3.2±1.3%	-4.3±2.7±0.7%
SK-IV	-5.3±2.0±1.4%	-3.4±1.8±0.6%
SK-I/II/III/IV	-4.2±1.2±0.8%	-3.2±1.0±0.5%

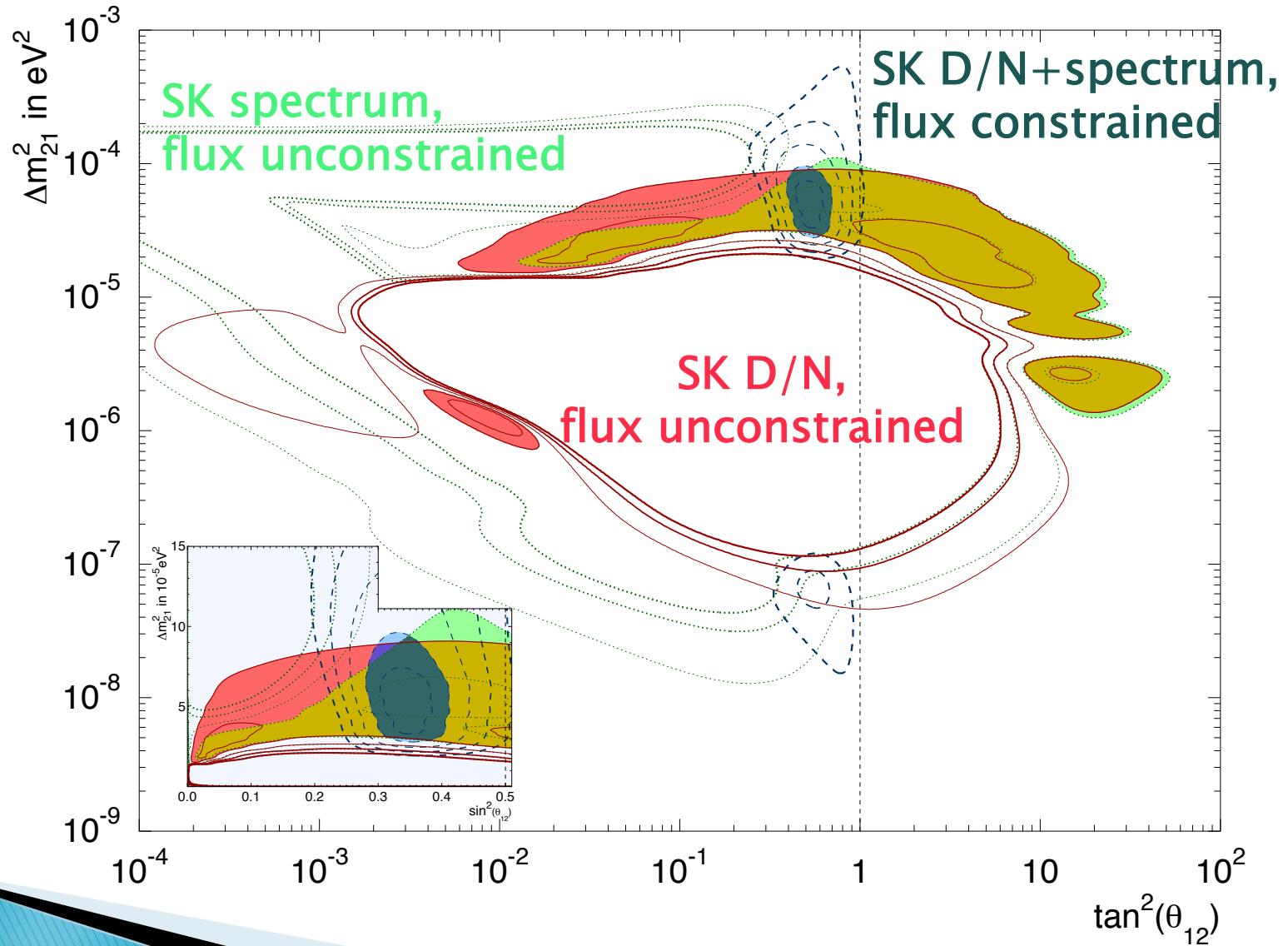
Day/Night asymmetry deviates from zero by 2.8 or 2.7 σ

- ▶ First significant indication for the solar neutrino day/night effect
- ▶ This is a “direct” indication for matter enhanced neutrino oscillation

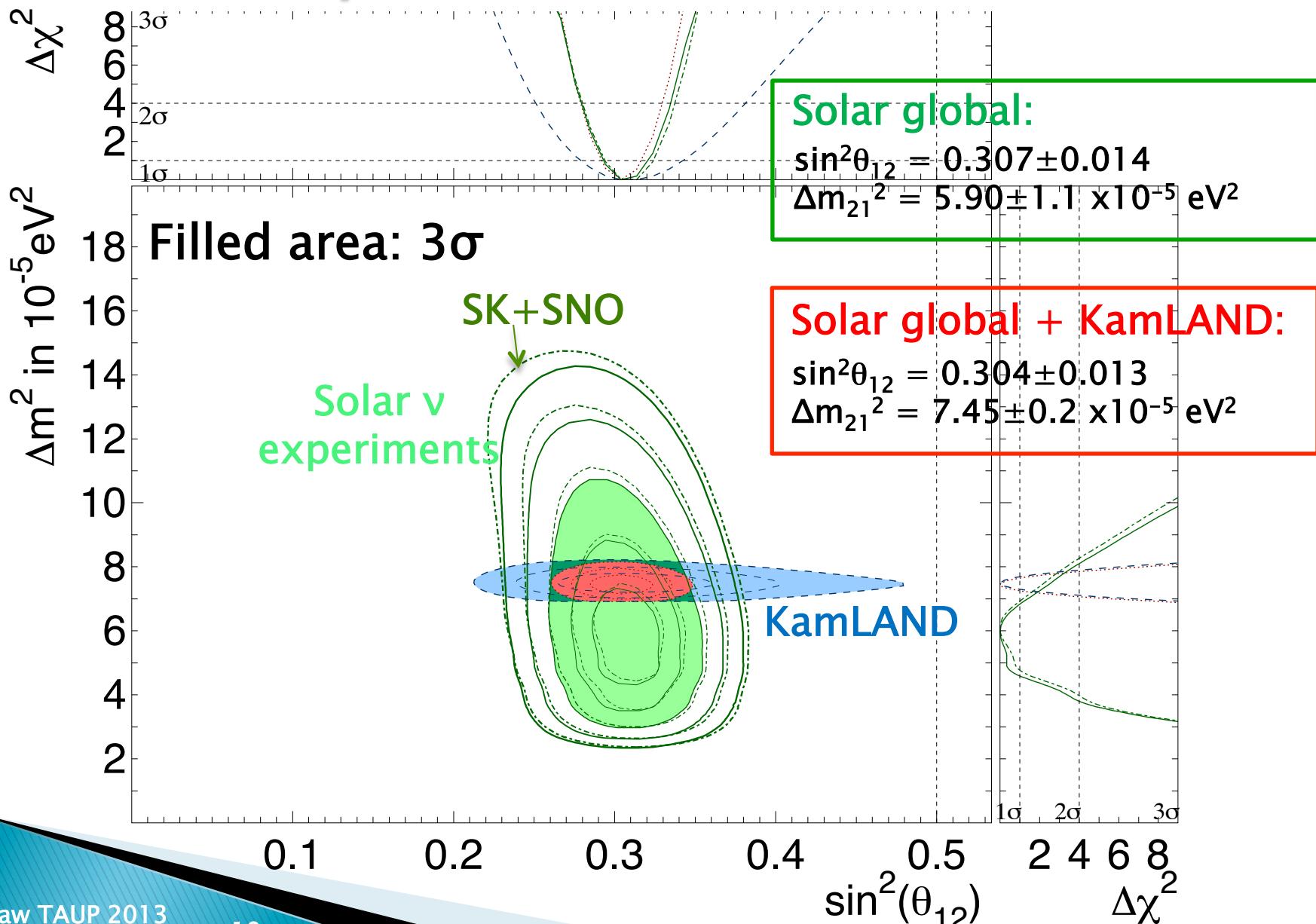
SK Day/Night Asymmetry



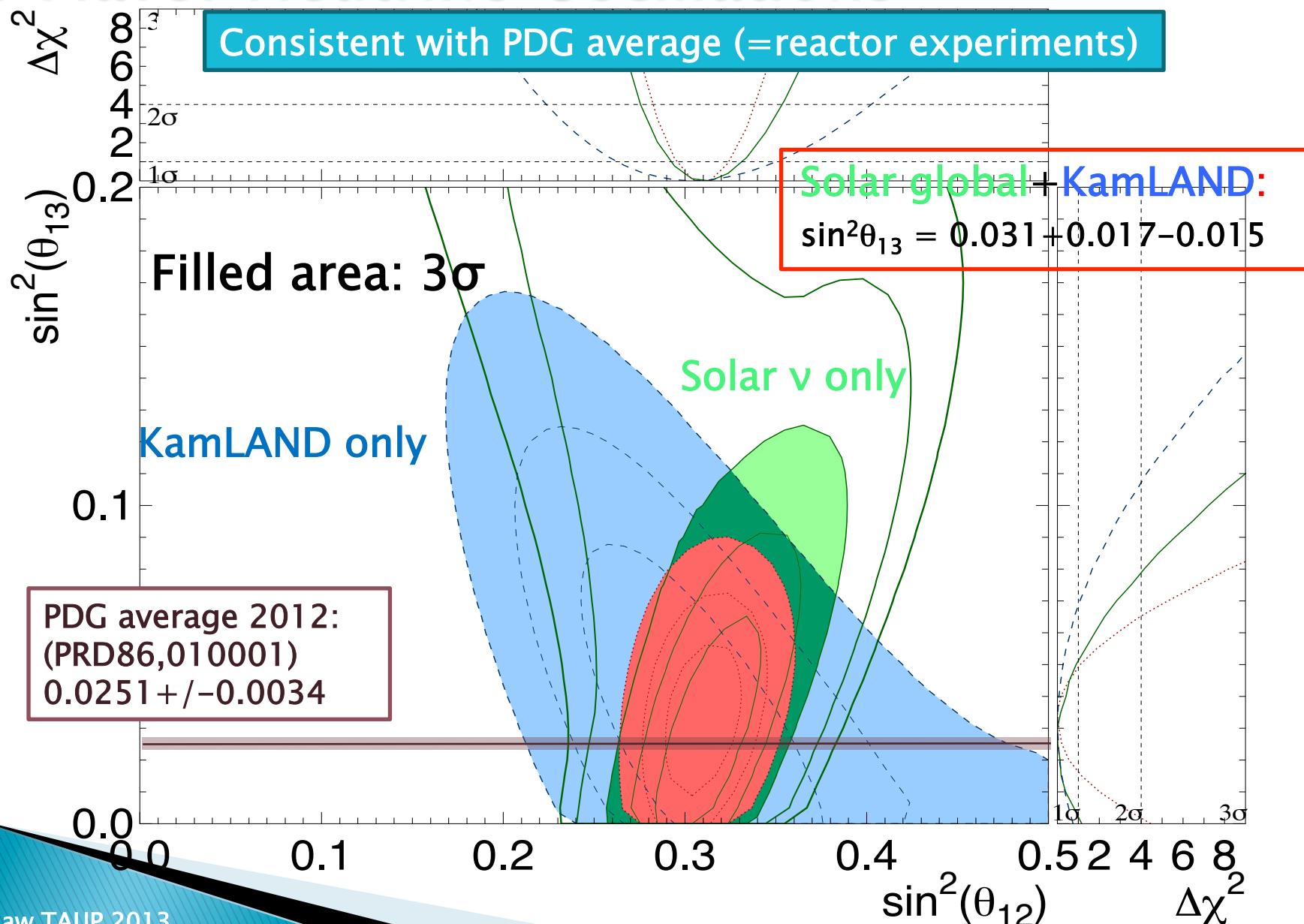
2 Flavor Neutrino Oscillations at SK



Global Analyses



3 Flavor Neutrino Oscillations



Conclusion

- ▶ SK solar neutrino flux measurements agree across all phases
- ▶ SK recoil electron energy spectrum slightly favors distortions
- ▶ SK measures the solar neutrino day/night asymmetry as either $-4.2 \pm 1.5\%$ or $-3.2 \pm 1.2\%$, 2.8 or 2.7σ from zero
- ▶ First indication for the solar neutrino day/night effect, gives “direct” indication for matter enhanced neutrino oscillation
- ▶ Solar global+KamLAND analysis gives:
 - $\sin^2\theta_{12} = 0.304 \pm 0.013$
 - $\sin^2\theta_{13} = 0.031 + 0.017 - 0.015$
 - $\Delta m_{21}^2 = 7.45 \pm 0.2 \times 10^{-5} \text{ eV}^2$